Correlating Sub-basin Sediment Fingerprints with Land Use in the Southern Piedmont

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Abstract. This study seeks to further our ability to directly determine sediment provenance by utilizing the sediment fingerprinting technique and Rapid Geomorphic Assessments (RGAs) to determine both sediment contributions from potential sources and the stability of stream channels. Two sub basins of the North Fork Broad River (NFBR) were sampled for suspended sediment. Potential sources fall into three categories 1: surface (pastures and forests) 2: stream banks 3: upland subsurface (dirt roads, construction sites). Three tracers are being used in the study: total Carbon (TC), ^{15}N, and Fatty Acid Methyl Esters (FAME). The Multivariate Mixing Model was used to determine relative contributions from source components. Results from the fingerprinting study were compared to RGA data in an attempt to establish a relationship between the two techniques. Currently we have sample data for 7 events in 2009 and 2010. Utilizing TC and ^{15}N, the model output suggests a contribution of about 85% from stream banks and another 10% from pastures. The upland subsurface category is showing only a minimal contribution of about 5%. RGA data collected in 2008 show both tributaries to be unstable with mean stability indexes ranging from 17.2 to 17.6.

INTRODUCTION

In the United States, 12% of assessed streams are considered threatened or impaired (USEPA 2006). In the Southeast, many Piedmont streams are considered impaired due to high sediment levels. These large concentrations of suspended sediment have an adverse impact on stream biota from primary producers to upper food chain predatory species (Dunne 1978). In an effort to reduce sediment loading, Total Maximum Daily Loads (TMDLS) and Best Management Practices (BMPs) have been developed for sediment and runoff control. In an effort implement TMDLs and BMPs in the Southern Piedmont, research is needed to better identify the source of these suspended sediments.

The Southern Piedmont had elevated rates of erosion during the intensive cotton farming era of 1830-1930 and as a result, channels and floodplains were inundated with the estimated 9.7 km^3 of soil that were eroded in the region (Trimble 1974).

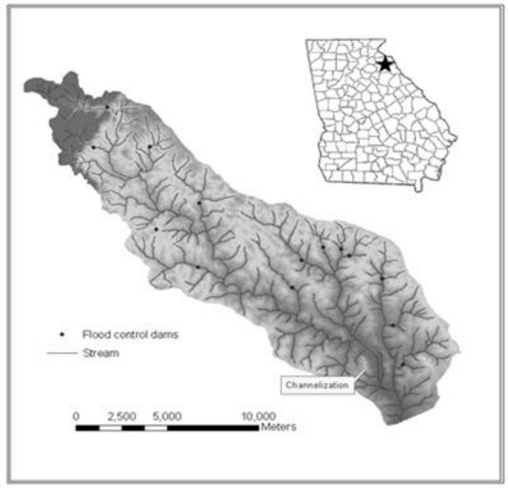

Figure 1. North Fork Broad River Basin

In modern times, erosion rates in the Piedmont have waned to levels approaching if not equal to their pre-European settlement rates because agriculture has waned and soil conservation measures have been put in place (Trimble 1974). It is apparent however that the effects of this period are still being felt as fluvial processes continue the task of transporting the *legacy sediments* deposited a century ago.

The North Fork Broad River (NFBR) is in Northeast Georgia. In 1998 it was placed on the 303(d) list for impacted biota and habitat with sediment being the pollutant of concern. In 2004 the USEPA conducted a macroinvertebrate study on the watershed. Based on the results of the study, the watershed was removed from the 303(d) list, however they reported that "habitat concerns are present but not to an extent impacting biota." In 2004 a grant was appropriated to implement BMPs and monitor sediment loads in the NFBR. A subsequent grant in 2007 funded our current research which involves the use of rapid geomorphic assessments and sediment fingerprinting to examine channel stability and determine the source contributions of suspended sediment. We are examining the spatial variability of sediment contribution among several sub basins of the NFBR in relation to the entire basin. Also, we are looking at the relationship between Rapid Geomorphic Assessment (RGA) values and bank contributions to suspended sediment with the hypothesis that higher bank contributions will be present in those basins whose channels seemed more unstable.

A previous study was conducted here by Mukundan et al. (2010) with the intent of determining the sediment contributions from different land use types for the main stem of the NFBR. Their results were that around 65% of sediment was of bank origin, 25% from upland subsurface inputs, and 10% from pastures. This study uses the concept of the channel evolution model in streams created by Andrew Simon and his associates (Simon and Hupp, 1986; Simon 1988). Simon's model was developed in western Tennessee in an attempt to understand process response mechanisms which followed channelization in that region. It was noted that upstream of disturbance (channelization) degradation was occurring with bed levels lowered up to 6 meters. Simon created a 6 stage model which documented the progression from pre-disturbance stable to post disturbance stable (or pre and post equilibrium) and is described in detail by Andrew Simon (1988).

Rapid geomorphic assessments (RGAs) are used to determine the stage of channel evolution and overall stability. The RGAs carried out in this study followed the channel stability ranking scheme (Klimetz and Simon, 2007). There are 9 criteria used in performing an RGA . These are: primary bed material, bed/bank protection, degree of channel incision (percentage) , degree of downstream constriction (percentage), dominant bank erosion type (fluvial vs. mass wasting), percentage of each bank failing, established riparian woody buffer (percentage), occurrence of bank accretion (percentage) , and finally the stage of channel evolution from Simon's model. A score above 20 indicates a very unstable reach; a score below 10 indicates a stable reach.

There have been numerous sediment fingerprinting studies in the past and it has proven itself an effective tool in determining sediment source type and spatial origin (Walling, 2005). The technique involves the characterization of source types based on chemical, physical and/or biological properties establishing individual source "fingerprints". The tracers used must be measurable in both source soils and sediment and must be conservative in that they don't undergo any chemical alterations between generation and delivery. Properties used include sediment color (Grimshaw and Lewin, 1980), plant pollen (Brown, 1985), mineral magnetic properties (Walden et al., 1997), rare earth elements (Kimoto et al., 2006), fallout radionuclides (Collins and Walling, 2002; Nagle and Ritchie, 2004; Walling, 2005; Mukundan et al.,2009), and stable isotopes of C and N (Papanicolaou et al.,2003; Fox and Papanicolaou, 2007), and Fatty Acid Methyl Esters (Banowetz et al., 2006)

METHODOLOGY

About 150 composite soil samples representing potential sediment sources were collected from spatially distributed locations in the watershed for ^{137} Cs and δ^{15}N analysis. Upland soil samples were collected from the upper 0 to 2 cm depth. Bank samples were collected from the bank face of actively eroding regions identified in the channel. The height of the channel varied from 1 to over 15 m at different locations of the watershed. Hence bank samples were collected by scrapping soil from bank faces that are potentially erodible under the current stream flow regime. Samples were collected from regions close to the water surface to about 1 m high. FAME (fatty acid methyl ester) analysis required another set of source samples. Samples were taken in both summer and winter to allow for seasonal variations in the surficial microbial population. These samples were taken using a 2.54cm diameter soil probe which was inserted to a depth of 2cm.

Most of the stream transport of suspended sediment occurs during storms, so it is critical to sample streams during storm events. The conventional method of suspended sediment sampling involves pumping large volumes of water samples (100 to 400 liters) from which about 20 to100 g of suspended sediment is collected by centrifuging (Walling et al., 1993). This can provide a composite sample with contributions from the different sources. In this study suspended sediment samples were collected during storm events by pumping water out of the stream and passing it through a continuous flow centrifuge collector mounted at the back of a pick-up truck. This method of sampling, in comparison to manual filtering, ensured that sufficient mass of suspended sediment was collected for all analyses. About 100 to 200 g of suspended sediment was required for a complete set of all physical and chemical analysis with a high degree of confidence. From the total amount of suspended sediment collected, about 50 to 100 g was used for ^{137}Cs analysis, 50-100mg for isotopic analysis, 3g for FAME analysis, and 40 to 50 g for textural analysis. All samples were air-dried and sieved through a 2-mm sieve.

The radionuclide tracer used in this study was ^{137}Cs. Our hypothesis was that soil surface samples (representing current erosion sources) will have relatively high activity due to fallout and soil samples from stream banks in flood plains (representing historic sources which were buried before the atomic bomb era) will have relatively low activity. Potential sediment sources identified in throughout the watershed included surface soil sources (croplands, pastures, and forested areas) and sub-surface soil sources (stream banks, unpaved roads and construction sites). Samples were analyzed for ^{137}Cs using a gamma ray spectrometry system with a high purity germanium detector at the USDA ARS Hydrology and Remote Sensing Laboratory, Beltsville, Maryland. The spectrometer measured the activity level in the soil and sediment samples.

For better discrimination between sub surface sources (bank vs. construction sites and unpaved roads), the stable isotope of nitrogen ^{15}N was used as a bio-geochemical organic fingerprint. Fox and Papanicolaou (2008) describe the applicability of ^{15}N to fingerprint sediment coming from source variables such as land-use, land management, geomorphology, and soil depth at a watershed scale. The stable isotope of nitrogen is expressed relative to the atmospheric nitrogen in "delta" (δ) notation indicating the difference between the sample isotopic ratio and the ratio in the standard as:

$$\delta^{15}N = \left[\frac{(^{15}N/^{14}N)_{\text{Sample}}}{(^{15}N/^{14}N)_{\text{Standard}}} - 1 \right] 10^3$$

where $\delta^{15}N$ is expressed in parts per thousand. Stable isotope analysis was done at the Odum School of Ecology, University of Georgia using a few milligrams out of 5 to 10 g of fine sediment that was ground and homogenized in a ball mill. A larger mass of sample ensured better representation of sediment originating from various sources.

While ^{137}Cs performs well at discriminating between surface and subsurface soils, it is an expensive tracer requiring a large mass (>50g) for analysis. We found Total Carbon (TC) to be an adequate replacement for ^{137}Cs based on correlation. As well as being less expensive, TC has the same mass requirement as ^{15}N which is considerably low at <50mg.

During our previous study (Mukundan et al., 2010), we found inter category sub surface discrimination difficult. That is, roads and construction sites are too similar for us to tell apart. In an urbanizing watershed, it might be useful to discriminate between the two. We attempted to utilize Fatty Acid Methyl Esters (FAME) as a biological tracer to discriminate between the two. Fatty acid methyl esters utilize fatty acids from the cell walls of microorganisms. Our hypothesis was that the differing environments present in dirt roads and construction sites would be host to different fauna and that this would allow us to discriminate.

Separate source samples were collected in both the winter of 2009 and the summer of 2010. Seasonal sampling was performed to allow for microbial community changes with each season. Samples were taken with a soil probe to a depth of 2.5cm. Care was taken to ensure no contamination occurred by flame sterilizing the probe between samples. Samples were dried and stored at -15C until ready for extraction. Around 10g of sediment was air dried each time a sample was collected and stored at -15C.

The extraction protocol we used for FAME is the "mild transesterification method" (Schutter and Dick, 2002). In this method, the fatty acids are placed in a highly alkaline solution of methanol. This causes saponification (the alkaline hydrolysis of an ester) to create a low-energy carboxylate anion from less stable hydroxide ion. The methanol contributes a methyl group, creating a fatty acid methyl ester. The "mild" method differs from the so-called "harsh" method because the trans-esterification is done at 37°C instead of 100°C.

Each sample produced a number of FAMEs. Principal component analysis (PCA) was utilized to reduce the dimensionality of the data. Plotting the first two principal components allowed a visual analysis of the data. The principal components were also used in the mixing model.

Soil and sediment samples collected from a wide range of locations may differ in texture. As a result, tracer concentrations can vary due to the relative proportion of the fine fraction, (i.e., clay and silt). Hence textural analysis was done on all the soil and sediment samples for expressing the tracer concentration in terms of the fine fraction in the samples. This ensured that the sediment samples and the soil samples collected from the banks and uplands were comparable. In our case, only TC needed particle size correction however as ^{15}N is a ratio and therefore not dependant on particle size.

Relative source contribution of suspended sediment was estimated by using a multivariate mixing model (Collins et. al 1998; Owens et al., 1999; Walling et. al., 1999).

The method of least squares was used for deriving the source proportions by minimizing the residual sum of squares for the *n* tracer and *m* sources using,

$$RSS = \sum_{i=1}^{n} \left[\frac{C_{sed\,i} - (\sum_{s=1}^{m} C_{s\,i} \cdot P_s)}{C_{sed\,i}} \right]^2$$

Where,

RSS = the residual sum of squares

$C_{sed,i}$ = the concentration of the tracer *i* in the sediment

$C_{s,i}$ = the mean concentration of the tracer property *i* in the source group *s*

P_s = the relative proportion from source group *s*

Davis creek and Freeman Creek are located in the upper half of the NFBR (Figure 2). RGAs were carried out on 5 reaches of Freeman creek on March 8, 2010 and 5 reaches of Davis creek on April 26, 2010. It is preferable to perform an assessment prior to the growth of grasses and leaf on conditions found after spring, however the assessments at Davis creek were performed under these conditions and required more attention and time to perform. Reaches were chosen to be representative and varied in length from 300 to 400 meters. Spatial coordinates were recorded and each reach photographed for documentation. Also, bed samples were collected for later particle size distribution analysis.

Primary bed material was determined visually as were the presence of bed/ bank protection. The degree of incision was determined by measuring the depth of the stream at the thalweg and dividing that by the average height of the bank from the top to the toe. Constriction is usually associated where obstructions or artificial protection are present; it is measured by determining width at the upstream and downstream ends of the reach and determining their relative differences. Dominant stream bank erosion processes were determined visually for both the left and right bank as well as the percentage of failing banks. These may be either fluvial (undercutting) or mass wasting (movement of large amounts of bank sediment at once). In order to classify a bank as dominated by mass wasting, 50% or more of the faces must exhibit this process. Vegetative cover is determined by judging the percentage of each bank with established woody vegetation. Grasses tend to be annual and provide no protection during winter months (Klimetz and Simon, 2007). Final index values were determined by tallying each of the scores from the 9 categories.

RESULTS

In the winter of 2009-2010, we collected 13 samples using the truck mounted centrifuge. 10 samples from Tom's Creek and 3 from Clarke's Creek (figure 2) An additional 3 samples were collected at Davis creek but were predominately sand and unusable.

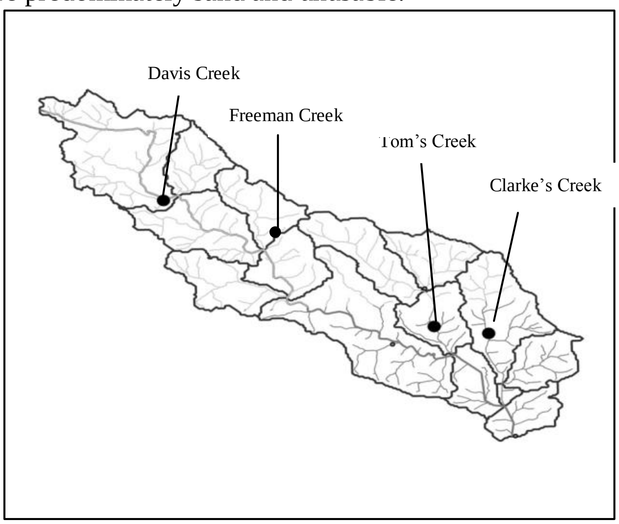

Figure 2. Sub-basin delineation and sampling sites.

MVMM results are listed in figures 3 and 4. Figure 5 illustrates the location in 2D space of both the sediment sources and the suspended sediment with respect to the tracers used in the study. Model results using ^{15}N and TC indicate about 85% of suspended sediment is of bank origin, 10% from pastures, and around 5% from upland subsurface origin. Results using ^{15}N and ^{137}Cs indicate about 63% of suspended sediment is of bank origin, 27% from pastures, and 10% from upland sub surface origin. While the intent is to examine each sub-basin independently, the current lack of samples for Clarke's Creek and the similarity of the two basins both in terms of land use and model results has led us to combine the two basins for the time being.

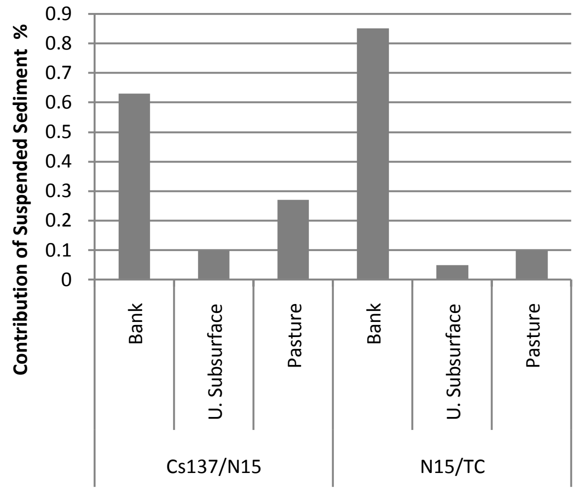

Figure 3. Sediment contribution using two sets of Tracers.

FAME results were mixed. While it was apparent FAME was able to easily discriminate source samples via PCA biplots, graphical and mixing model results indicate suspended sediment is predominately of forest soil origin which we believe to be false. Currently 40 source samples and 5 sediment samples have been examined. A replicate set will be analyzed in the beginning of 2011 to confirm these results.

RGA results for the two tributaries we have fingerprinting data for are listed in table 1. RGAs were performed in the winter of 2008-2009. The results show that both streams have relatively unstable channels.

Cross-section number	Stage of channel evolution	Channel stability index
1	V	20.5
2	V	17.5
3	V	17
4	V	18.5
5	V	17
6	V	18
7	VI	14.5
8	VI	14.5
9	III	15.5
10	III	16.5
11	IV	22.5
12	III	19
13	III	18
14	III	18
15	VI	15
16	III	16.5
	mean Clarkes	17.1875
	mean Tom's	17.625

Table 1. RGA results from Tom's And Clarke's Creek.

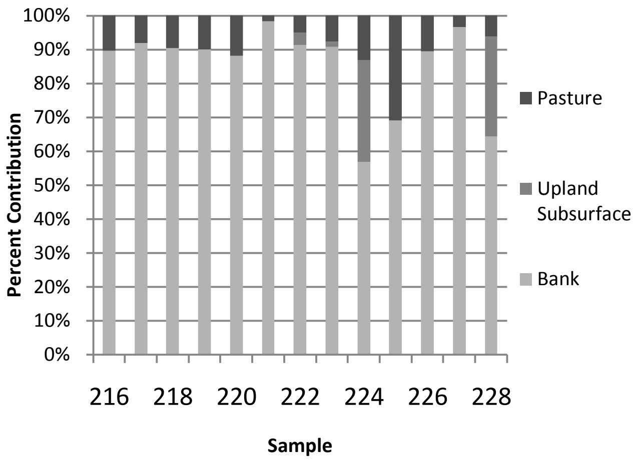

Figure 4. Individual sample relative source contributions.

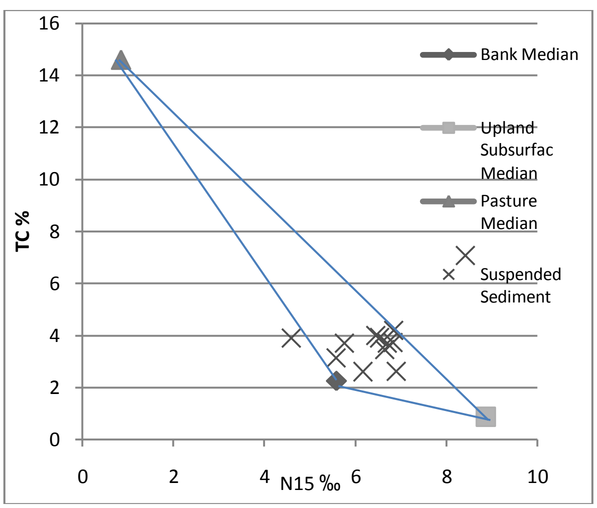

Figure 5. Scatter plot of sediment values with source values.

DISCUSSION AND CONCLUSIONS

The usefulness of the fingerprinting technique has been demonstrated in many studies. Our intentions with regards to this study were to first attempt to increase our resolution with respect to sediment origin in our study basin, second to pair the fingerprinting technique with RGAs in an attempt to better explain the channel processes taking place in the NFBR and third to attempt to find a more affordable tracer suite.

Increased resolution within a watershed will allow planners the ability to pinpoint areas which are in need of their attention. In this study two sub basins were selected. The results indicated the sediment loads in these basins were dominated by bank sediment at around 80%. This agrees with the RGA analyses of the two tributaries which suggested active bank erosion was taking place. By combining the two techniques within a watershed, sediment contribution values can be compared to the stability of the channels. This allows for a determination of areas where bank erosion may be dominant and therefore sediment loads more difficult to reduce.

The use of TC as a fingerprinting tracer was demonstrated in this study. It has proven a valuable tracer as it is a viable substitute for ^{137}Cs which is both expensive and requires a large mass for analysis. Combining TC with ^{15}N allows us the discriminatory power needed with the potential to forego centrifuge as a means of sediment collection. It is our plan to begin to include automatic water samplers in our sampling strategy. This will allow us to sample multiple streams within the watershed simultaneously for each event.

FAME proved to be effective at discriminating source soils. However, we were unable to attain attractive results with sediment. FAME analysis requires separate source sampling in multiple seasons. Also, it may be necessary take samples on a yearly basis in order to assure that the microbial populations haven't shifted. The extraction procedure itself is also time consuming. These factors did not lend themselves to FAME being an effective tool in this study.

It is our intention now to begin performing uncertainty analysis on the MVMM. Monte Carlo simulations using @RISK software should provide us with a distribution of potential sediment contribution values for each sample. This technique should provide us with the statistical power we need to confirm our results.

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